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Recent Developments of Aircraft Nondestructive Evaluation Based on Advanced Sensor Techniques

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Abstract

The safety and structural integrity are of great importance to military and commercial aircraft, and the developments of effective nondestructive evaluation (NDE) methods are receiving much attention in recent years. The objective of this paper was to provide the recent developments of aircraft NDE based on advanced sensor techniques: (a) Ultrasonic testing with piezoceramic sensor arrays, air-coupled transducers, and dry-coupled transducers; (b) Eddy current testing with SQUID magnetometer sensors, Hall effect sensors, and giant magnetoresistive sensors; (c) Optical testing techniques including thermography with infrared sensors, laser shearography with CCD sensors; (d) Other NDE methods including microwave testing with waveguide sensors, vibration monitoring with fiber optic sensors, and magnetic resonance testing with NMR sensors. The characteristics of these sensor techniques and the corresponding NDE methods were reviewed combining various practical applications in aircraft materials and structures. The developing trend of the advanced sensors based aircraft NDE methods was directed.

Keywords: Nondestructive evaluation, Aircraft, Sensor, Development

1. Introduction

Aircraft structures are susceptible to fatigue cracks, corrosion damages and impact defects during service in harsh environmental and working conditions, leading to a tendency to catastrophic failures of critical structural components if not detected and repaired. The problem of guaranteeing reliable and efficient checks has received great attention for early detection of aircraft structure defects to prolong the service life by necessary maintenance operations, especially for aging aircraft. In addition to safety, the cost is a major concern, and typically 27% of an aircraft's life cycle cost is spent on inspections and repairs, excluding the opportunity cost associated with the time when the aircraft is grounded [1]. Furthermore, a lot of advanced materials including composite structures have been used in aircraft industry [2], thus resulting in new problems for the structural integrity inspections. Therefore, there has been an increased emphasis on and non-destructive evaluation (NDE) for aircraft [3], which play important roles in the entire process from aircraft structural design to the manufacture and subsequent maintenance, till the final structural failure or retire.

Various advanced aircraft NDE techniques have been developed to date in addition to the conventional ultrasonic and eddy current testing methods. These NDE techniques involve many key technologies, among which advanced sensors are necessary to monitor the vibration, ultrasonic wave, magnetic field, temperature, strain, displacement, etc. The sensors used for NDE systems have different working theories, types, sizes, weights, sensitivity, costs, numbers, arrays and locations, which affect the sensitivity, efficiency and safety of the overall systems. In recent years, great progress has been made in aircraft NDE and the related sensor techniques, and the objective of this paper was to review the recent developments of the advanced sensor techniques based NDE in aeronautical fields, including ultrasonic testing, eddy current testing, optical testing, and some other testing methods.

2. Aircraft NDE based on advanced sensor techniques

2.1 Ultrasonic testing and the sensor techniques

Ultrasonic testing (UT) is one of the primary methods for aircraft NDE, and the recent progress in correlative sensor techniques involves piezoceramic sensor arrays, air-coupled transducers, and dry-coupled transducers.

2.1.1 UT with piezoceramic sensor arrays

As for ultrasonic testing, the number, location and network of the transducers greatly affect the overall system performance and cost. Sparse leave in place sensor array and computed tomography with through transmission guided waves were used for structural health monitoring (SHM) of E-2 aircraft wing, and an artificial saw cut defect was clearly detected and localized [4]. During the testing, eight small lead zirconate titanate transducers (0.25 inch diameter, 10 mils thickness, 400 KHz) were distributed evenly on a 240mm diameter circle on the wing skin, and each of the transducers could act as both transmitter and receiver. To improve the ultrasonic sensor network performance for E-2 aircraft wing monitoring, they also proposed a quantitative sensor placement optimization method with covariance matrix adaptation evolutionary strategy (CMAES) and a damage detection probability model [5]. The sensors were not preferred to be on the regions of stiffening ribs since these were the infeasible spaces for the decision variables. With optimized sensor number and distribution decisions, CMAES was very valuable for the SHM sensor network onto real aircraft structures. Zhao et al [6] developed a wireless, in-situ ultrasonic guided wave SHM system with an eight element 350kHz piezoelectric (PZT) transducer array attached to the inner surface, and the array was about 10 inches in diameter and evenly spaced. The collected ultrasonic guided wave data were successfully transferred from the onboard SHM device to a ground PC station wirelessly to achieve a near real-time data collection and display for E-2 aircraft wing inspection. The data collected with this device, showing good signal quality for defect detection and localization, were almost identical with those collected through a direct-wire connection.

Rajagopalan et al [7] used a Lamb wave based SHM system with a single transmitter and multiple receivers (STMR) coupled to one side of the aircraft multi-layered composite plate to identify and locate defects. The receivers in the STMR array of transducers were arranged in a circle with a transmitter placed at the center, and a phase reconstruction algorithm was proposed to process the data and reconstruct the images. Additionally, Sekhar et al [8] adopted a multi transmitter and multi receiver (MTMR) technique using smart flexible sensor patches with built-in network of piezoelectric wafer active sensors. The conventional cross-hole tomography effectively monitored the disbonds of elevon stiffeners, and the modified cross-hole tomography gave lateral extent of the damage for barely visible low velocity impact damages on composite structures like wing and aileron.

2.1.2 UT with air-coupled ultrasonic transducers

With a magnetic Flock of Birds sensor to acquire positional information of the transducer, a QMI Sonda Airscan based air-coupled ultrasonic C-scan system has been developed and tested by a research group in Iowa State University [9-11]. Transmitting and receiving piezoceramic air-coupled transducers (120 kHz and 400 kHz) were attached to a yoke to operate in a through transmission mode. Field tests have been conducted on Airbus A320 spoilers, Boeing 737 trailing edges, MD-80 trailing edges, Black Hawk helicopter rotor blade, and other composite sandwich structures with various defects. Being simple, portable, easy to use, relatively inexpensive, non-contact and non-contaminating, the system has proven to be a good NDE tool for aircraft composite honeycomb structures. Recently, a more robust Generic Scanner (GenScan) system was demonstrated using a sonic triangulation device as the position encoder [12]. To date, the GenScan system has been used together with Panametrics/Krautkramer flaw detectors or Nortec/Zetec eddy current instruments for corrosion depth and crack detection of composite structures.

Carbon/carbon composite aircraft brake disks were inspected by Im et al [13] utilizing QMI Sonda Airscan ultrasonic system. The transducer used was piezoceramic and a pair 400kHz focused probes with 25.4 mm in diameter. Visual, qualitative C-scan images were acquired for the entire nonuniformity in thickness direction of the composite, and the air-coupled transducers were used to measure the composite's ultrasonic velocity successfully.

2.1.3 UT with dry-coupled ultrasonic transducers

Modern aircraft structures contain advanced materials that are sensitive to water, gel or other couplants, thereby flexible polymers have been used to couple with PZT transducers through dry interfaces. However, most of the dry-coupled systems operate at a relatively low frequency range up to 1 MHz due to substantial attenuation and multiple reflections. Several types of dry-coupled transducer polymer modules for the transmission of both longitudinal and transverse ultrasonic waves at high frequencies up to 10MHz were developed at Northwestern University [14]. The dry-coupled films were very flexible, and could be adapted to the irregular inspection surfaces even with a low pressure. Among the three different types of the polymer films developed, the epoxy protective layers could minimize the ultrasonic signal loss at the transducer-film interface, showing the best compatibility with the commercially available contact transducers. The prototype modules with polymer films have been integrated with the portable ultrasonic inspection units and successfully tested on a number of aircraft structures, including porous materials and coatings at normal/elevated temperatures as well as components with limited access and various spatial orientations.

2.2 Eddy current testing and the sensor techniques

Eddy Current testing (ET) is widely used for electrically conductive aircraft material on the basis of the great progress of various sensor techniques, such as SQUID magnetometer sensors, Hall effect sensors, and giant magnetoresistive sensors.

2.2.1 ET with SQUID magnetometer sensors

In order to explore the testing procedures for extremely thick-walled aircraft structures, German researchers [15-16] conducted pulsed eddy current inspections of Boeing 737 wheel and Airbus A380 wing splice samples using superconducting quantum interference device (SQUID) magnetometers, and a typical flaw (length 30 mm, depth 31-46 mm) in a 62 mm thick bolted three-layer aluminum sample was successfully inspected. Compared with the conventional induction coil sensor, the magnetometer sensor could record the transient data at later times, corresponding to information from deeper sample layers and higher depth sensitivity.

2.2.2 ET with Hall effect sensors

TRECSCAN transient eddy-current scanning system [17] has been developed for NDE of subsurface cracks and corrosion in thick airframe structures. The probe comprised a pancake drive coil inside a ferrite cup-core, with a commercial Hall-effect device mounted on the axis of the coil between the coil and the specimen. Hall sensors produced an output voltage proportional to the component of the magnetic field that was perpendicular to the device averaged over the area of the sensor, providing a significantly better sensitivity to low frequency components of the transient signal compared with conventional coil sensors whose sensitivity was frequency dependent and reduced to zero at DC.

2.2.3 ET with giant magnetoresistive sensors

A portable giant magnetoresistive (GMR) sensor ET system has been tested on aircraft fuselage lap joints samples with simulated EDM notches [18], and the results showed a high reliability of detecting defects 0.5 inch in length and 0.01 inch in depth. Unlike the conventional ET with a pickup coil, the crack signals in terms of DC voltage by the GMR sensor system were easy to understand for determining the crack depth and length.

2.3 Optical testing and the sensor techniques

During the past several years, optical testing methods based on advanced sensor techniques have achieved great progress for aircraft NDE, including thermography with infrared sensors, laser shearography with CCD sensors.

2.3.1 Thermography with infrared sensors

Avdelidis et al [19-20] developed a pulsed-transient thermographic set-up with an integrated flash heating system and an Indigo Merlin mid-wave (3-5μm) infrared camera with a cooled InSb detector to image surface or near surface defects of aircraft composite structures. Excellent results were achieved on the detection of subsurface features of aluminium and/or carbon fiber reinforced plastic (CFRP) struts located beneath relatively thin CFRP skins (2 or 4mm) and aluminium alloy skins (1.6mm). Since aluminium alloy skin was more sensitive to thermal contact resistance than CFRP material, the thermal images of the strut beneath CFRP skin were obtained far more easily than those beneath aluminium alloy skin.

Sonic infrared imaging technology could inspect various cracked aircraft components using a 40 kHz ultrasonic transducer and an InSb array infrared camera (Indigo Phoenix) [21]. The ultrasonic caused fatigue crack faces to rub or clap, and induced frictional heating and temperature increasing that could be detected by an infrared camera and appeared as bright infrared source within a dark background field. Sonic infrared was capable of detecting diverse fatigue cracks in JT-8D aircraft engine turbine blades, Boeing 767 wheel half, brake key, bolt, and brake manifold, etc.

To detect active fretting damage on hidden faying surfaces of two fastened Al 2024-T3 sheets of aircraft fuselage joint structures, Forsyth et al [22] used pulsed flash thermographic method with a commercial system Echotherm. The illumination head was a closed hood in which two xenon flash lamps and flash reflectors were positioned. The infrared camera, a Therma CAM SC 3000 by Flir Systems, was a quantum well infrared photo detector (QWIP) with a focal plane array detector of 320 × 240 elements, a thermal sensitivity of 20mK at

303K and a spectral response from 8.0 to 8.8 μm. Live thermal imaging was achieved for the specimens to identify fretting damage in all examined cases, with the results better than ultrasonic testing methods.

2.3.2 Laser shearography with CCD sensors

Laser shearography is a reliable coherent-optical NDE method using a laser light source to illuminate the object and providing the speckle pattern of surface and sub-surface flaws by an electronic sensor, e.g. charge-coupled device (CCD). Kalms et al [23] developed a comprehensive shearography device with the object illuminated with two mutual incoherent laser sources to successfully inspect the laminates and honeycomb structures for aircraft wing and fuselage. The laser sources illuminated more than a half of the object area, and both mutual incoherent waves produced their own reference beam by shearing, resulting in two independent interferometric sensitive speckle fields for each area observed by the shearographic CCD sensor. Pandurangan et al [24] utilized a full-field surface slope measurement technique (shearography) to inspect bonded metallic GRID-LOCK joints, and the defects such as disbond and weak bond could be clearly identified in the out-of-plane displacement gradients (shearograms) obtained by a CCD camera. Besides, surface displacements of the specimen's top surface were also measured using a custom-built optical scanning system with a CNC XY table (from a Sherline Model 2000 vertical milling machine) and a non-contact fiber optic displacement sensor (Philtec RC-89).

2.4 Other testing methods and the sensor techniques

In addition to the above UT, ET and optical testing methods, other new NDE techniques involve microwave testing with waveguide sensors, vibration monitoring with fiber optic sensors, and magnetic resonance testing with NMR sensors.

2.4.1 Microwave testing with waveguide sensors

Microwave (e.g. centimeter and millimeter wave) can penetrate inside low-loss dielectric materials to detect subsurface defects such as inclusion and corrosion with dielectric property variations. Abu-Khousa et al [25] presented the theoretical image formation model describing the interactions between microwaves and multi-layered structures, and illustrated its potential on optimizing the detection capability of subsurface inclusions in multi-layered composites. The near-field microwave images with phase dynamic range of 120° and a resolution of 1 mm in *x* and *y* directions were obtained using K-band open-ended rectangular waveguide as imaging sensors operating at 25.5 or 26GHz. Gupta et al [26] used near-field microwave reflectometers with open-ended rectangular waveguide probes at V-band (50-75GHz) and W-band (75-110GHz) to evaluate corrosion under paint of lap joint like structures. The DC output voltage of the reflectometer was proportional to the changing phase and magnitude of the reflected signal measured at the probe aperture. The resulting matrix of DC voltages was normalized and plotted as grayscale images with relatively fine spatial resolution. To detect and quantify the laser machined pittings in aluminum panels, high-resolution raster scanned millimeter wave images were obtained by Ghasr et al [27] using a phase sensitive reflectometer at V-band (50-75 GHz) and a dielectric waveguide probe with the aperture dimensions of 1mm × 0.5mm. Optimizing the dimensions and shape of the probes could provide better radiation and better matching to the feeder waveguide, thereby improving the sizing accuracy. The sensitivity of single open-ended waveguide probe was limited by the standoff distance variations for detecting corrosion under paint, hence Ghasr et al [28] developed a new differential probe consisting of a millimeter wave source, a 3dB power divider, two identical waveguide aperture probes, a power combiner, and a detector. The output of this probe represented the coherent difference between the reflected signals picked up by each aperture, and was not affected by standoff distance changes as much as a single probe. The sensitive differential probe could detect not only the edges of the corroded area, but the inner parts of the corrosion patches. A rectangular waveguide probe and several near-field millimeter wave reflectometers operating at 26.5-75GHz (mainly Ka- and V-bands) were used to detect aircraft honeycomb composite panels with glass fiber reinforced plastics skins [29]. The raster scanned C-scan images, with high spatial resolution, revealed most of the subsurface flaws, even some overlapping flaws, but it was not possible to determine the flaw depth information quantitatively since the near-field probes were uncalibrated and produced at single frequencies. Without couplants, the portable, inexpensive, small millimeter wave probes could facilitate fast on-line real-time inspections for aircraft NDE.

2.4.2 Vibration monitoring with fiber optic sensors

Several NDE methods can be used for aircraft structure health monitoring, of which vibration monitoring is effective for special structures such as aircraft wings. Leng et al [30] developed a smart structure system to monitor structural damage by spatial speckle detection of multimode fiber optic vibration sensors. Smart aluminum specimen surface with mounted fiber optic sensors and smart carbon/epoxy composite specimens with embedded multimode fiber optic sensors were investigated, showing effective results for SHM under service conditions. With low cost, high sensitivity with long sensing lengths and big sensing area, the fiber optic sensors were light and small enough to be embedded within or on the surface of aircraft structures in a non-obtrusive manner.

2.4.3 Magnetic resonance testing with NMR sensors

Honeycomb sandwich structures are vulnerable by water ingress leading to degradation and eventual failure of some aircraft panels [31]. A new approach based on nuclear magnetic resonance (NMR) was proposed by Marble et al [32-33] to detect the water in sandwich panels by a portable Bruker 0.36 T MOUSE sensor approximately 10×10×10 cm^3 in size and weighed about 1.5 kg. The bar magnets in opposing orientations provided a static magnetic field, and a solenoidal coil centered between the magnets generated a RF field, resulting in an orthogonal zone with a small dome-shaped sensitive volume of 0.5cm radius × 1mm thickness over the coil. The magnets were joined together on the bottom side of the instrument with a ferromagnetic yoke. The portable one-sided magnetic resonance technique was successful to obtain high-resolution magnetic resonance images of water in sandwich panels with Nomex or aluminum honeycomb cores and graphite-epoxy skins. With an optimized unilateral NMR sensor, this approach would conduct in-situ testing for the critical areas of sandwich panels.

3. Summary and outlook

The safety and structural integrity are greatly important for military and commercial aircraft, thereby the developments of effective NDE methods have received much attention in recent years to reduce the manufacturing/maintenance cost and prolong the service life. Various low cost, high efficiency and high reliability NDE methods have been developed and successfully applied to aircraft fields, not only for aging aircraft, but also for new aircraft with advanced materials such as honeycomb sandwich composites. Every testing technique has its advantages and defects, and a combination of several methods may be preferred for some specific inspections by rational selection and comparison. Modified ultrasonic and eddy current testing, together with new techniques such as optical and microwave testing can play important roles in aircraft NDE.

Advanced NDE methods are based on advanced sensor technologies of different types and principles, which have been studied extensively in recent years. Various high performance sensors have provided new opportunities for scientists and engineers to devise cost-effective miniaturized NDE systems with higher resolution, faster response and far greater reliability than conventional NDE techniques.

Structural health monitoring is a new paradigm with early warning to prevent catastrophic failure and define remedial strategies, thus reducing maintenance costs and increasing aircraft safety. The most promising SHM techniques need advanced smart sensors, such as small PZT sensors, fiber optic sensors, easily embedded to or bonded on critical aircraft structures unobtrusively. Condition based maintenance strategy on the basis of real time in-situ SHM will be the future direction of the aircraft NDE and maintenance philosophy.

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